TECHNICAL RELEASE
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DESIGN OF OPEN CHANNELS

CONTENTS

TECHNICAL RELEASE No. 25, CHAPTER 6. APPENDIX A.

Stream Armor Design Concepts

Purpose

This appendix (1) explains the underlying physical processes affecting armoring, (2) describes different SCS-approved math models available, and (3) presents an example illustrating one way to estimate armoring.

The various math models for critical and recommended allowable tractive stress discussed in this appendix are accepted in the engineering profession; they differ mainly in choice of a safety factor, scope of application, or both. Two different math models for recommended allowable tractive stress are used in SCS. They differ solely in their safety factors. The armor designer is free to select the most applicable model.

Actual transverse tractive stress of each situation must be determined through a hydraulic analysis. The example in this appendix uses a simplistic model to determine the hydraulic radius. In real situations, actual cross-sectional geometry and, possibly, precise water surface profile calculations are required. However, this requirement does not invalidate the concepts illustrated by the example.

Physical Processes

Armoring is a well-known natural phenomenon. Furthermore, its important features already are used in some engineering structures, for example, riprap. Armoring is sometimes called hydraulic sorting. It is a limiting or special case of sediment transport. It has been studied by various scientists over the years, (e.g., A. Shields, A. Strickler, E. Lane, H. Einstein, and others). Understanding the primary principles of armoring is still developing and is leading to various math models and procedures for field application.

Armoring is the result of the dynamic interaction of unsteady fluid flow and a mobile bed composed generally of a broad range of discrete particles.

At low flows, the boundary is stationary; as the flow increases, however, the smallest particles begin to move. As the flow increases further, larger particles also begin to move but at a lower velocity. Finally, the discharge can increase to a point where the entire boundary is moving, although the larger particles move more slowly than the smaller. As the flow decreases, the process reverses itself; but if the smaller particles are not replaced, the bed is left degraded and coarser.

Armoring occurs when smaller particles are transported from the boundary but not replaced and coarser particles are exposed but not transported. Whether true armoring occurs depends on whether the exposed coarser particles originated at their present position or upstream. If they originated upstream, what has occurred is not armoring but sediment transport by unsteady flow.

A design of a stable channel that depends upon armoring for stability can be a contradiction unless the armor surface has already been established and will not be disturbed during construction. Otherwise, degradation must occur before a complete armor surface can exist, and resulting eroding bed material contributes a downstream sediment load to the system. Furthermore, this degradation causes undercutting of the toes of the bank, which can lead to bank sloughing. Ultimate design value of armoring may be that it is the last line of defense against the more extreme events that otherwise may completely unravel a channel and possibly lead to ecological disaster or catastrophic failure of important cultural features.

Math Models

The math models developed by Shields and Strickler provide the basis for the armoring design procedure. The procedure was verified by Lane's field work. The designer must analyze (1) the active or driving forces and (2) the passive or resisting forces. The analysis of active forces consists of determining the hydraulics or depth of flow and determining the boundary roughness shear or tractive stress. The latter determination is necessary because not all energy loss is due to boundary roughness. Bends or changes in cross-sectional area cause energy loss through internal fluid shear.

SCS has adopted Manning's equation to estimate the rate of total energy loss (S_e); i.e.,

$$S_e = [(Q\ n_e)/(1.486\ AR^{2/3})]^2$$

where

$n_e \equiv$ retardance coefficient for total energy loss.

Furthermore, SCS has adopted the Manning-Strickler equation to estimate the energy loss due to boundary roughness, (S_t); i.e.,

$$S_t = [(Q\ n_t)/(1.486\ AR^{2/3})]^2$$

where

$n_t = K_m d_m^{1/6}$ the Strickler equation -- retardance coefficient due to boundary roughness only.

$d_m \equiv$ a characteristic boundary particle size.

$K_m \equiv$ empirical coefficient relating d_m to n_t.

Units for K_m must be consistent with units chosen for d_m.

Report 108 of the National Cooperative Highway Research Program recommends using $K_m = 0.0395$, with $d_m = d_{50}$ expressed in feet. The K_m value is the same as the default value for C_n in Eq. 2 of TR-59, "Hydraulic Design of Riprap Gradient Control Structures."

This leads to the following formula for actual average transverse stress ($\bar{\tau}_{act.}$):

$$\bar{\tau}_{act.} = \gamma R\ S_t$$

where

$\gamma = 62.4\ \#/ft^3$

$R \equiv$ hydraulic radius, ft.

$S_t = (n_t/n_e)^2\ S_e$; Eq. 6-3, TR-25.

Shield's work establishes the critical relationship between the active and passive forces; i.e., it relates the critical fluid tractive stress (τ_c) for incipient motion to the gravitational resisting force. It was verified for coarse grained materials ($d_m > 6$ mm) by Lane's study of prototype field canals and for discrete particle material ($d_m > .1$ mm) by Report 108.

Lane reports:

Critical tractive stress, $\tau_c = 6\ d_m$; where d_m is in feet and τ_c is in psf.

This critical tractive stress is nearly identical with Shield's work for $d_m > \frac{1}{4}$ inch.

Lane recommends:

Allowable tractive stress, $\tau_{all.} = 4.8\ d_m$; d_m, τ_c same units as above.

This allowable tractive stress is conservative with respect to Shield's work for $d_m > 4$ mm and gives results identical to those from Eq. 6-5 of TR-25.

Report 108 reports:

Critical tractive stress, $\tau_c = 5\ d_m$; d_m, τ_c same units as above.

This critical tractive stress is conservative with respect to Shield's work for $d_m > 4$ mm.

Report 108 recommends:

Allowable tractive stress, $\tau_{all.} = 4\ d_m$; d_m, τ_c same units as above.

This allowable tractive stress is conservative with respect to Shield's work for $d_m > 2$ mm and gives results identical to those from Eq. 24 of TR-59, setting the FS value equal to 1 and using the default value for C_{50}.

For armoring design analysis, the characteristic armor particle size (d_m) is chosen from the coarser portion of the original material since most of the fine material will be hydraulically removed. Usually $d_m = d_{90}$; therefore, m = 90. Furthermore, for design purposes, all material smaller than the d_m is assumed to be sorted out. Therefore, the depth of degradation (D_d) is

$D_d = d_m/[(100 - m)/100] = 10\ d_{90}$ (see page 6-31).

This assumption has a physical interpretation. The d_{90} size of the original bed material (before armoring) will become the d_{50} of the final exposed surface bed material (after armoring).

Example

This example illustrates the armoring design concept. The uniform flow-unit slice assumption was made for convenience in computing the depth of flow; it may not be valid for most field applications. Furthermore, it is not a conservative assumption, from a stability viewpoint, for sub-critical but supernormal flows. Also, the choice of the numeric value for the modifying value (n_o), which accounts for energy loss due to factors other than boundary roughness, should be determined reach-by-reach for each application. (See NEH-5, Supplement B, for guidance). The smaller the n_o value, the more conservative the design from a stability viewpoint.

Problem: A concrete emergency spillway is planned to discharge onto an alluvial valley floor of at least 6 feet of homogeneous material. What maximum steady-state unit discharge would limit scour by permitting armoring to the d_{90} size material? What would be the expected depth of scour? The valley slope (S_o) is 0.00520 ft/ft, the d_{90} is 110 millimeters, and the modifying value (n_o) is assumed to be 0.005. Assume uniform flow-unit slice principles are applicable; therefore, the hydraulic radius is equal to the depth of flow ($y = R$), the rate of total energy loss is equal to the valley slope ($S_e = S_o$), and the actual transverse tractive stress is uniformly distributed ($\bar{\tau}_{act.} \leq \tau_{all.}$). Use the recommended allowable tractive stress formula from Report 108 that is compatible with TR-59. Use $K_m = 0.0395$.

Given:

$S_o = 0.00520$

$m = 90$

$d_m = d_{90} = 110 \text{ mm} = 0.3609 \text{ ft.}$

$n_o = 0.005$

Required: (a) q_{max} for $\bar{\tau}_{act.} = \tau_{all.}$

(b) D_d for $m = 90$

Solution: (a) $n_t = K_m d_m^{1/6}$

$= 0.0395(0.3609)^{1/6}$

$= 0.0333$

$$n_e = n_t + n_o$$ (see 7th step, page B.6, Supplement B, NEH-5)

$$= 0.0333 + 0.005$$

$$= 0.0383$$

$$S_e = S_o = 0.00520$$

$$S_t = (n_t/n_e)^2 \; S_e$$

$$= (0.0333/0.0383)^2 \cdot 0.00520$$

$$= 0.00393$$

$$\tau_{all.} = 4 \; d_m$$

$$= 4 \cdot 0.03609$$

$$= 1.444 \text{ pounds per sq. ft.}$$

$$\tau_{act.} = \tau_{all.}$$

$$\gamma R \; S_t = 4 \; d_m$$

$$R = (4 \; d_m)/(\gamma \; S_t)$$

$$= 1.444/(62.4 \cdot 0.00393)$$

$$= 5.884 \text{ ft}$$

$$y = R = 5.884 \text{ ft}$$

$$q_{max} = (1.486/n_e) y^{5/3} \sqrt{S_o}$$

$$= (1.486/0.0383)(5.884)^{5/3} \sqrt{0.00520}$$

$$= 53.6 \text{ cfs/ft}$$

(b) $$D_d = d_m/[(100 - m)/100]$$

$$= 10 \cdot 0.3609$$

$$= 3.61 \text{ ft}$$

Therefore, the maximum steady-state unit discharge that would limit scour by permitting armoring is approximately 54 cfs/ft. The expected depth of degradation before complete armoring (one layer) is almost 4 feet.